How to Make Chance Manageable: Statistical Thinking and Cognitive Devices in Manufacturing Control

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0 Introduction

The industrial enterprise is an excellent place to view a great diversity of forms of control: control of finances and accounts, controls on the material operations of fabrication, of logistics, and control of people at every level. Managerial knowledge seeks very explicit control objectives and their study is thus particularly fruitful for one interested in the history of techniques and in the sociological aspects of control. These modes of control are embodied in often very complex plans and devices which exist, at one and the same time, as ideas (they have been conceived by humans, they are founded on certain bodies of knowledge), and in material form (written texts, numbers, graphs, measuring instruments, software applications, etc...)

We propose then to address the problem of the birth and diffusion of management knowledge from another perspective: that of the *devices* or *objects* through which this knowledge acquires a certain materiality. Without wishing to deny the importance of ideas, it is useful to examine as well the role played by material objects in the construction of ideas and in their diffusion and application in the world of business.

By “devices” or “objects”, we mean all material or graphic concrete forms which are produced in support of specific knowledge, and which might be used as an illustration, an argument, a proof, or means of application. Graphical representations hold an important place among these objects, as one can observe in leafing through any management manual. The *manual*, a particular type of book, is also a specific object which plays a certain role in the diffusion of knowledge, a role generally little studied in the domain of management (while the history and sociology of science and technology is interested in this sort of object). The application of knowledge, as in “time and motion studies”, requires particular instruments (special timepieces, equipment for recording the scene, data sheets..). One can also think of software objects (for example, the packages of statistical tools for the control of quality).

We will examine the role played by objects in the edification of managerial knowledge from three points of view:

- in the construction of management theories, both as elements of the development of knowledge and as means of support of the rhetoric of their promoters (these two aspects being difficult to dissociate in practice);
- in the application of knowledge, as mediators with respect to action; the properties of knowledge for action are in fact tied to objects;
- in the diffusion of managerial knowledge: being the material side of knowledge, they are engaged in the social life in the same manner as any other object; for example, they can have the form of merchandise and be subject to circulation, commerce, and exchange.

We adopt a constructivist’s and ecologist’s conception of what is usually called the “production/ diffusion” of knowledge in management: this knowledge, constructed under certain unique conditions by a group of promoters, is put in circulation within the social domain by means of objects (mock-ups, models, texts of different kinds...); entering into the world of the firm, they are subjected to a process of selection which brings into play the properties which the objects appear to bear. This analysis puts the accent on the interactions among, on the one hand, the objects which are produced and put into circulation, and, on the other hand, the contexts which give sense to the objects and establish their properties.

Let us say a few words about the role objects play within an organization. Researchers in organizational science have frequently studied the unanticipated effects[1] of managerial tools, for example some systems of budgetary control or control by objectives: The meaning of these control systems is transformed by their users according to their local context, which sometimes leads to results which differ in quite significant ways from what was intended at the outset. Today, an interest in objects, and the way in which they are "engaged in action", is manifest within the social and cognitive sciences[2] by those who study the role of objects and the environment in the coordination of individuals at work; we see interesting parallels developing with respect to organizational science. From this perspective, an industrial organization is not only a collection of abstract procedures (rules) which coordinate its people, but also and above all, an assemblage of material plans and devices which make the doing of real activities possible. A management or organizational method is a composite of ideas, abstract principles, and objects or methods of practical import which engage the individual bodily and mentally in the execution of certain procedures. The control of the organization over its members is effected largely through these objects and methods: its members must understand and learn to use them in a way conforming to the intentions of the management. One can thus see the objects as signs (in the sense defined by C.S. Peirce): they do not possess in themselves any literal meaning but their meaning is constructed by the members of the organization, through processes of social interaction under certain circumstances in relation with their work (or with other preoccupations). One of the challenges of managerial control is thus to frame these interpretations, to limit their reading which could turn them against the aims of the organization. We know that one of the most prevalent forms of worker resistance is to use the objects of work away in illegitimate and/or unauthorized ways. We are thus led to study all the social processes which reveal, establish or identify the properties of objects.

Here we consider the case of statistical methods of quality control in industrial manufacturing. The relevant objects in this case are of a cognitive type: they give form to information (data) in a way which enables certain operations which would not be possible

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[1]For example, Berry, M., 1983: “Une technologie invisible? L’impact des instruments de gestion sur l’évolution des systèmes humains”, Centre de recherche en gestion, Paris.

[2]See notably the thematic edition of the journal *Raison pratique*: Les objets dans l’action. De la maison au laboratoire, Ed. de l’EHESS, Paris, 1993.

Hutchins E., 1990: ”The Technology of Team Navigation” in: Galegher J., Kraut B., Egido C. (eds): *Intellectual Teamwork: Social and Technical Bases of Collaborative Work*, NJ: Hillsdale, Lawrence Erlbaum Associates.

without them. These objects are based upon scientific knowledge, a knowledge which they bring onto the shop floor, but they shape and represent this knowledge so that it is not evident in the object's day-to-day use; it enters only in special occasions.

Desrosieres[3] has ably characterized the double aspect of statistical objects with respect to action -- and this statement might hold for many cognitive artefacts:

> "Statistical tools permit the discovery or the creation of things which serve as a basis for describing the world and acting upon it. One can say of these objects, at one and the same time, that they are real and that they have been constructed, from the moment they are taken up in other assemblages and circulated as things in themselves, cut from their origins, this which is, after all, the fate of all manner of products."

Statistical methods of quality control were developed in the decade of the 20's to meet the needs of the American telephone industry at AT&T, Western Electric and at Bell Laboratories; in their final form, as a standardized technique, they appear as "control charts" which allow one to track the consistency of manufacturing performance and detect early on the deregulation of a machine.

The principle of the control chart is relatively easy to understand, but requires some explanation. In order for a manufactured object to be judged of "good quality", a certain number of its characteristics which have been selected as critical measures of quality -- for example specific geometric dimensions -- ought to satisfy some specified tolerances. But the machinery of production, as precise as it may be, is incapable of producing objects *exactly* alike; in fact, the characteristics of the fabricated products are distributed according to some statistical distribution. All goes well as long as the distribution of each characteristic remains within the limits set by the tolerances; one then says that the machine is *under statistical control* or *well set*. But it always happens at some time or another that the machine goes off.

Suchman L., 1987: *Plans and Situated Actions: The Problem of Human-Machine Communication*, New York: Cambridge Univ. Press.

[3]Desrosières A., 1993: *La politique des grands nombres. Histoire de la raison statistique*, La Découverte, Paris, p. 9.

When this deregulation is progressive, the machine begins to produce some bad pieces among the majority of good pieces. The control charts are a graphical tool which, with the aid of sampling techniques, allows one to detect this deregulation very early on, before it affects a large number of fabricated parts. One can then, with confidence, interrupt the fabrication process to reset the machine and thus avoid the production of scrap as well as the cost of rework later on -- a cost which can be very high. The control charts are today a fundamental tool for tracking quality in fabrication, principally in the context of quality assurance procedures..

1 The control of fabrication prior to the “probabilistic revolution”

The principal innovation introduced in the 20’s in the control of fabrication was *taking chance into account* by the methods of mathematical statistics which allowed the rational definition of procedures for making sampling decisions. As we shall see, this step constitutes, in the field of industrial production, a veritable “probabilistic revolution”.[4]

Prior to the 20’s, there evidently existed some procedures for the control of quality, even some which made use of sampling, but they did not explicitly rely upon probability theory.[5] At the beginning of the XXth century, *determinism* was the dominant notion among those engineers and scientists who turned their attention toward industrial organization. The example of Henry Le Chatelier illustrates how, in this way of thinking, it was impossible to take chance into account. Le Chatelier, an eminent chemist, member of the French Academy of sciences, is also recognized for his role in diffusing the work of F.W. Taylor in France. He declares, in the preface of a book on scientific management[6]:

> “All phenomenons are interwoven according to some inexorable laws... The belief in the necessity of laws -- that is, in the non-existence of chance -- leads in industry to a continual struggle against irregularity, against the

[4]Kruger L., Daston L., Heidelberger M. (eds), 1987: *The Probabilistic Revolution*, Cambridge: MIT Press.

[5]Stigler S.M., 1977: “Eight Centuries of Sampling Inspection: the Trial of the Pyx”, J. Am. Stat. Ass., vol. 72, pp. 493-500.

> wastes of fabrication and, in almost all instances, allows one to eliminate all such irregularity and waste."

The opinion of Le Chatelier *vis a vis* chance is explained by his conception of shop management. Only one way appears to him to be legitimate and fertile: to know, with as great an exactitude as possible, the laws of the material put into play in the fabrication process by the machines... Neither his conception of quality nor his ideas about industrial organization have need of, one might say paraphrasing Laplace, a "hypothesis of chance". On the contrary, one must reject chance with the greatest vigor because it offers an easy way out for the managers of a factory who show a distaste for taking the laborious and costly path of scientific knowledge which would render a true account of phenomenons. To accept the idea that chance exists is to refuse to banish disorder.[7]

Sometimes, notably when control required a destruction of the product (e.g., rupture test), it was necessary to take a sample of the pieces. Le Chatelier did not consider the question of what the size of this sample should be nor did he consider the validity of conclusions that one might draw from the test; he probably was incapable of treating these questions because he seemed to have ignored the theory of probabilities, a subject that Laplace, however, had very clearly articulated along with a deterministic philosophy, at the beginning of the XIXth century[8].

The same deterministic conception seemed to have reigned as well in American industry. F.W. Taylor gave an example of a perfectly deterministic organization of quality control in the fabrication of bicycle ball bearings[9]. Also in 1916, Nusbaumer[10] had followed the plan of Taylor to a "T" in reorganizing a gun powder manufacturing plant for which he was

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[6]Nusbaumer E., 1924: *L'organisation scientifique des usines*, Nouvelle librairie nationale, Paris. Preface of H. Le Chatelier.

[7]The debate is still ongoing with the partisans of "zero default". Certain people see the approach of statistical control of manufacturing as the institutionalization of inefficiency: the machine operators, knowing that the products are inspected at the end of the production line, do not particularly seek to correct any defaults. The primary intent of a policy of "zero default" would be to force the workers to coordinate their activities.

[8]Laplace P.S., 1986: *Essai philosophique sur les probabilités,* 1825, reed. Christian Bourgois, Paris.

[9]Example to be found in: *The Principles of Scientific Management.*

[10]Nusbaumer E., 1924: *L'organisation scientifique des usines*, Nouvelle librairie nationale, Paris.

responsible. Even with respect to those subjects which, from today's perspective, lend themselves remarkably well to a probabilistic approach, such as the preventive maintenance of power transmission belts in a shop with the aim of avoiding interruptions of the fabrication process, Taylor adopts a rigorously deterministic approach[11].

The faith in determinism in the American industrial milieu was equally supported by research of the greatest possible precision in the mechanics of fabrication, which appeared as the only way to obtain the interchangeability of parts. The historian A.D. Chandler notes:

> "The American system of manufacturing can be defined as production process of large quantities by means of fabrication of standardized parts which are assembled into the final product."[12]

For much of industry, one of the principal objectives regarding quality in mechanical processing was the interchangeability of components according to the "equation": quality = interchangeability = precision. The non deterministic approach to the control of fabrication developed at Bell Laboratories would overthrow this dominant scientific ideology within industry and introduce an approach based upon statistical physics into the field of engineering.

2 The construction of a solid theory of quality.

2.1 Why Shewhart?

If this was a purely historical approach, it would be necessary to describe and analyze a very large variety of works which appeared over the decade 1920-30, not only in the United States, but also in France, in Germany, in Great Britain, and perhaps also in Russia. It is in fact remarkable that, in a very short period of time in these different countries, but independently, engineers had considered probabilistic approaches to the control of quality.

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[11]Taylor, F.W., 1907: "L'emploi des courroies", in: *Etudes sur l'organisation du travail dans les usines*, Dunod et Pinat, Paris.

[12]In: Mayr O. and Post R.C. (eds) 1981: *Yankee Enterprise. The Rise of the American System of Manufactures*, Smithsonian Institution Press, Washington, D.C., p. 153. The whole of this book shows the primary importance

This suggests that the emergence of the problem did not result from a train of circumstances within a single industrial sector, but is more probably tied to a historical stage in the evolution of production techniques, in the organization of the firm, and in industrial exchange. Without great risk of self deception, one might propose that it is a matter of the spread of mass production ideas and techniques, recognizing that a characterization so general will not suffice as an explanation. To give a more satisfactory response would require extensive research, more extensive than is the ambition of this text.

Among all these independent efforts, those of Bell Laboratories hold our attention for the following reasons: It is there that the most ambitious and most complete body of theory was developed; there too the applied method embodied in the control charts in fact moved into industry; there too the published materials are very numerous and rich and allow us to follow the trace of development of this innovation. In the other countries, on the contrary, the methods that were developed remain fragmentary or limited to certain firms and have been definitely superseded by the method of Bell Labs. There is one notable exception: the English were able to climb aboard the train and integrate their own efforts with the American approach, to which they have considerably contributed in the years 1930 -- which is not astonishing considering the impressive potential of their researchers in statistics.

In order not to complicate our exposition, we limit ourselves to the methods of the control charts; but complementary methods of quality control by acceptance sampling were also developed at Bell Laboratories during the same period of time.[13]

W.A. Shewhart (1891-1967) is the recognized creator of control charts, as attested by a dozen articles appearing between 1924 and 1931, culminating with a treatise[14] which assembled all of his previous work in one place. From one article to another one can easily follow the evolution of his ideas and his associated tools, and it is this construction that we will analyze,

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of the question of interchangeability of parts and the astonishment of the industrial world when confronted with the performance of american manufacturers in this matter.

[13]Bayart D, “Savoir organisationnel, savoir théorique et situation: le contrôle statistique sur échantillon”, *Entreprises et Histoire*, 1996, No. 13, 67-81

[14]Shewhart W.A., 1931: *Economic Control of Quality of Manufactured Products*, New York: Van Nostrand and MacMillan, London.

addressing particularly three stages of this development: 1924, 1926 and 1929-30[15].

Western Electric was preoccupied during the years 1922-24 within the *Engineering Department* with problems of quality control[16]. W.A. Shewhart, a physicist by training, schooled in the methods of statistical physics, was charged with the task of examining measures to apply to telephone equipment with aim of developing procedures for quality control. He was transferred to Bell Labs when they were created in 1925 and there continued his work on quality control.

2.2 The carbon microphone, or setting the stage for randomness: 1923-24.

In the first sentence of his first lengthy article, before any talk of control charts, Shewhart makes a frontal attack on the belief in determinism, redefining the significance of the measure of any physical magnitude basing this on the modern physics of his time. In place of exactitude, that is to say a precision as fine as one wishes, one can only hope to find some statistical entities which no longer provide certainty but only probability:

> “We ordinarily think of the physical and engineering sciences as being exact. In a majority of physical measurements this is practically true. ... With the introduction of the molecular theory and the theory of quanta, it has been necessary to modify some of our older conceptions. Thus, more and more we are led to consider the problem of measuring any physical quantity as that of establishing its most probable value. We are led to conceive of the physical-chemical laws as a statistical determinism to which “the law of great numbers” imparts the appearance of infinite

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[15]Shewhart W.A., 1924: “Some Applications of Statistical Methods to the Analysis of Physical and Engineering Data”, *Bell System Technical Journal*, vol. III, No. 1, 43-87

Shewhart WA, 1926: “Quality Control Charts: a brief description of a newly developed form of control chart for detecting lack of control of manufactured products”, *Bell System Technical Journal*, vol. V (1926), 593-603

Shewhart WA, 1930: “Economic Quality Control of Manufactured Product”, communication Am. Assoc. Advancement of Science, Des Moines, Dec. 1929, published in *Bell System Technical Journal*, vol. 9 (1930), 364-389.

[16]Fagen M.D., (ed), 1975: *A History of Engineering and Science in the Bell System, The Early Years (1875-1925)*, vol. 1, Bell Telephone Laboratories. Chapter 9: “Quality Assurance”.

> precision."[17]

Shewhart transfers the approach used in statistical physics to the field of engineering of the telephone. The two first paragraphs of the article are entitled in a symmetrical way: "Statistical nature of certain physical problems" and "Statistical nature of certain telephone problems". In the first, he uses an account of the historical experiments of Rutherford and Geiger (1910), showing that alpha emission by a radioactive source is a random variable following a determinate statistical law. In the second, he shows, with graphical support, a telephone component whose behavior appears to be random and concludes:

> "The characteristics of some telephone equipment cannot be controlled within narrow limits much better than the distribution of alpha particles could be controlled in the above experiment."

This comparison legitimates the transfer of probabilistic and statistical thinking from the field of science to the field of telephone engineering. The recourse to probabilistic models becomes even necessary on the part of scientific researchers at AT&T, whose mission is to stay well informed of the state of the art.

The object chosen by Shewhart furnishes a particularly illustrative example of why one needs a statistical approach. The carbon microphone is a key element of the telephone system and posed many problems at that time[18]. One of his important characteristics, namely its electrical resistance, shows all the appearances of random behavior, even though measured in a laboratory with all imaginable care. The impotence of a deterministic approach to this kind of object is clear: randomness is found at the heart of the manufactured object and not just in the machines which make it.

This providential object gives Shewhart the opportunity to emphasize a fundamental problem in quality control: what standards of fabrication can one establish for products whose characteristics of quality can not be fully controlled in a deterministic way? And how then

[17]Shewhart, 1924, pp. 43-44.
[18] Fagen, 1975, *op. cit.*

does one formulate and represent these characteristics for personnel in the shop? How to establish the limits of allowable variability? Shewhart's response is "by using statistics and only by such means". This then provided the basis for his pursuit of research in this field in order to arrive at some operational methods for use on the shop floor. At the same time, with this example, he is able to denounce the belief of industry according to which one could indefinitely increase the precision of machines so as, *in all cases*, to resolve questions of quality.

Let us see now how this radical questioning opened up matters. Because it does not suffice, in the industrial domain, to denounce established ideas but requires proposing some useful, working methods, Shewhart proposes an approach in this article, and one which he is adopts in the following, which consists of identifying, by numerical methods, the statistical distribution of the chosen characteristic of quality under stable conditions of manufacturing. The greater part of the article is thus devoted to a review of existing statistical methods with the aim of evaluating their relevance to identifying an empirical distribution. Thus it is a methodological and problem setting article. The practical tools of work are not yet the focus, but they soon make their appearance in the course of this year, 1924.

2.3 From statistical distributions to control charts

The 1924 article concludes that the quality of an industrial product may be represented by a statistical distribution which is identified by the numerical values of the first moments, according to the mathematical theory of Karl Pearson. Starting from there, Shewhart is going to progressively put this into the form of graphical tools -- the control charts -- which will be the essential material object of this method. It is this evolution which we are going to retrace, beginning with the initial idea appearing in an internal memorandum[19] dated 16 May, 1924, and ending with the standardized form of 1935. Our analysis aims to show that the graphic form has constituted a fixed element with respect to which theoretical conceptions have evolved around as a pivot. This observation supports and confirms the thesis to wit: the predominant role of objects in the evolution of ideas in management.

[19]Note reproduced in Fagen, 1975, *op. cit*.

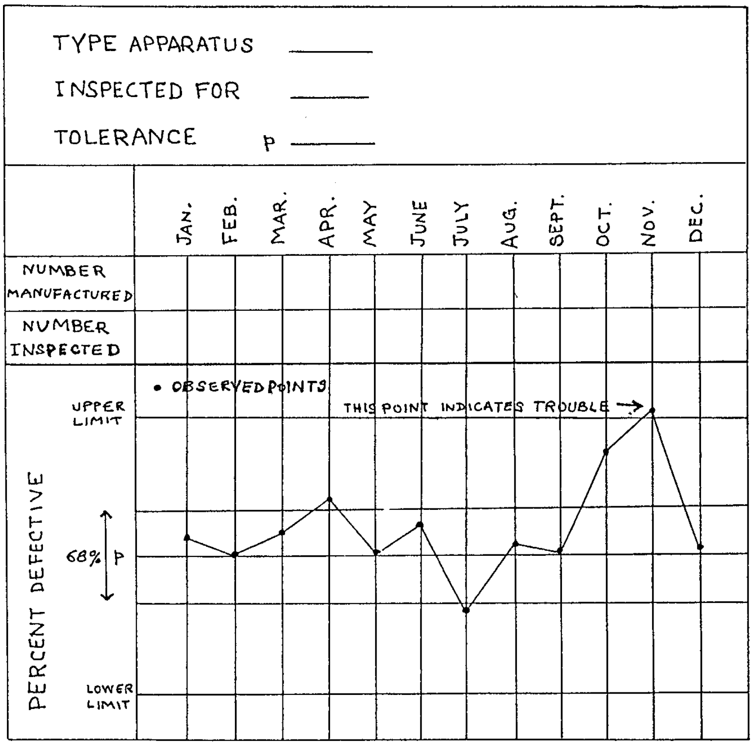

Figure 1 – The original idea of a control chart (1924)

The internal memorandum of 1924 has two elements: an example of the graphical representation (fig. 1) and a very brief text of Shewhart indicating that he is on the path toward developing an operational method:

> "The attached form [graphical representation] of report is designed to indicate whether or not the observed variations in the percent of defective apparatus of a given type are significant; that is, to indicate whether or not the product is satisfactory."

He adds that the underlying theory is relatively complex and that he has begun work on a memorandum which would explain it in detail. But it is clear that this graphical form is the major contribution because it permits one "to see in a glance the most pertinent information". Its principle is simple: a horizontal axis represents the successive dates of the measurements made, while the vertical axis shows the scale of the measured characteristic. The new element, which renders the graph valuable, is the couple of horizontal lines whose ordinate corresponds to theoretically determined values and which represent limits not to be exceeded;

if the value of the measured characteristic reaches either of those lines, this indicates a problem (Shewhart has written “this point indicates trouble” on the figure).

A posteriori, knowing the underlying theoretical developments, it is easy to understand the leading idea: given a statistical distribution, one may deduce from probability theory an interval within which the variable falls with a probability very close to 1.0. If then the result of a measurement falls outside of this interval, it is most probable that a change occurred in the statistical distribution -- this being the *trouble* highlighted by Shewhart:: something is out of line; it requires intervention. But before he arrived at such a clear conception, Shewhart began with the construction of a sophisticated theory closely related to the work of the British biometricians. He laid it out in 1926, employing for the first time the term *control charts*.

His objective, as in his first article, is to identify the empirical distribution of the quality characteristic. The method includes four steps: choice of a theoretical model for the distribution (normal law, Poisson law, etc.), choice of estimators, numerical estimation, test of significance. This methodology requires much too arduous calculation to be used on a routine basis in a shop, but it takes advantage of the graphical display principle of 1924, yet with a difference: this time, it shows a display for each of the parameters characterizing the assumed distribution (Fig. 2). The parameters are calculated for a sample of each month’s production and drawn on the graphic. The horizontal lines show the limits within which each parameter should stay, provided the statistical distribution remains unchanged. They also include sampling fluctuations. One clearly sees on Fig. 2 important variations for some months, which correspond to variations in the fabrication process.

It is striking, in regarding figure 2, how the distribution of the quality characteristic changes over the period of observation: the four first moments of the distribution displace significantly from the limits corresponding to the fluctuations of the sample. The graph thus makes extremely visible the existence of important causes of variations in the fabrication process.

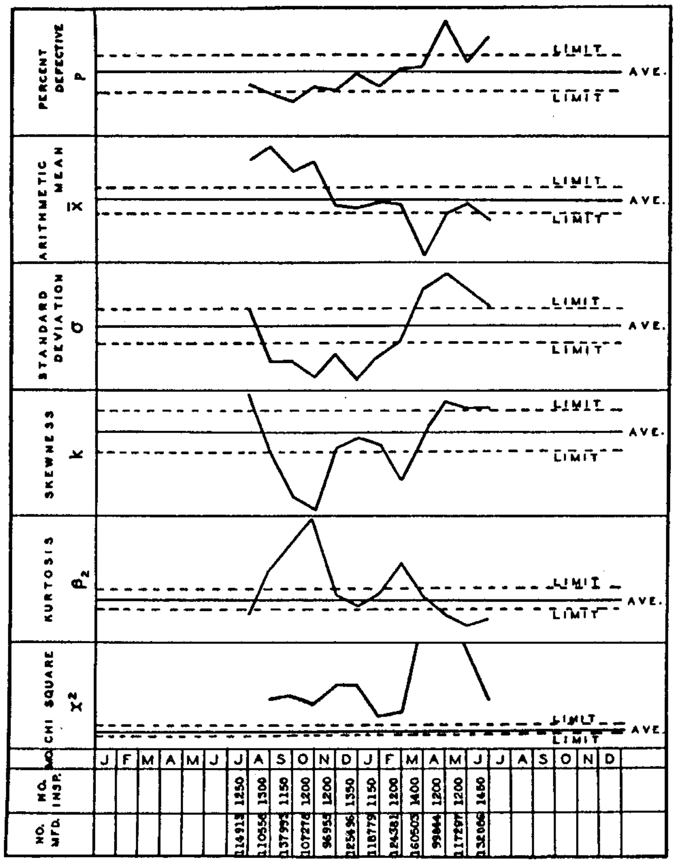

Figure 2- A control chart for the parameters of a statistical distribution (1926)

At this stage, Shewhart has thus constructed two instruments: one simple and eloquent graphical representation and a methodology which is dense and requires much calculation. These two facets are not yet fully complementary: the graph illustrates the theory but doesn't contribute to it. The evolution of the method which ensues is very interesting in that the theory is going to be considerably simplified and the graphical tool is going to become an integral part of the whole. This evolution calls to mind that process Simondon has called *concretization*[20] of a technical object: A technical object is first thought of then realized as a prototype, as a representation of a theoretical scheme (here, the Pearsonian theory); then, with time and with use, its components are redefined as a function of one another -- a process which confers to the object the appearance of an autonomous life, relatively independent of the theoretical conceptions which have presided over its creation.

This concretization clearly shows itself in the normalized forms of the control charts (1935[21], fig. 3) The primitive form uses all of the first four moments of the distribution in order to avoid the hypothesis of its normality, at the cost of very heavy calculation. We see that the standardized method only uses the first two moments; what occurs then with the normality hypothesis? The manual defining the standard says quite briefly that “in practice, the mean and the dispersion are considered sufficient”[22]. The process of concretization has thus led in the present case to a simplification of the initial object for the domain of application of the method, secured at the price of an implicitly restrictive hypothesis, in the theoretical domain.

TABLE II.—OPERATING CHARACTERISTIC, DAILY CONTROL DATA.

SAMPLE	SAMPLE SIZE, n	AVERAGE, $\bar{X}$	STANDARD DEVIATION, σ
No. 1	50	35.7	5.35
No. 2	50	34.6	5.03
No. 3	50	32.6	3.43
No. 4	50	35.3	4.55
No. 5	50	33.4	4.10
No. 6	50	35.2	4.30
No. 7	50	33.3	5.18
No. 8	50	33.9	5.30
No. 9	50	32.3	3.09
No. 10	50	33.7	3.67

Central Lines

For $\bar{X}$: $\bar{X}' = 35.00$.

For σ: $\sigma' = 4.20$.

Control Limits

For $\bar{X}$: $\bar{X}' \pm 3\frac{\sigma'}{\sqrt{n}} = 35.00 \pm 1.78$,

33.22 and 36.78.

For σ: $\sigma' \pm 3\frac{\sigma'}{\sqrt{2n}} = 4.20 \pm 1.260$,

2.940 and 5.460.

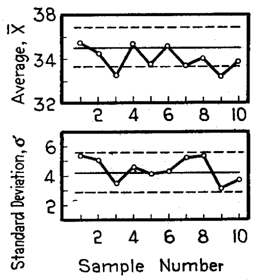

FIG. 2.—Control Charts for $\bar{X}$ and σ.
Large samples, $\bar{X}'$, σ' given.

RESULTS: Lack of control at standard level indicated on third and ninth days.

Figure 3- The standardized form of the control chart (1935)

Similarly, the procedure for determining the statistical distribution is also standardized, codified in an operational procedure where one searches to minimize the references to statistical theory. The very open method that Shewhart had presented in 1926 has thus, ten years later, taken the tangible form of a graphical object in accord with a *mode of application*. This object, having become to a great extent autonomous with respect to the statistical theory at its base, is now ready to be routed through the institutional channels for diffusion throughout the industrial world: for standardization, use in training.... Even though

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[20]Simondon G., 1969: *Du mode d’evolution des objets techniques*, Paris, Aubier.

[21]American Society for Testing Materials: *Manual on Presentation of Data, Supplement B*, 1935.

[22] In the meantime, Shewhart had conducted many experiments with his “bowls” (cf *infra*), and this conclusion is rather empirical.

these channels, as we shall see, have not been the only means of diffusion, they have played an important role in identifying and making known the control chart "product".

2.4 From epistemological ambitions to economic advantage.

But Shewhart was not content to simply propose some operational rules and tools. His ambitions went beyond those of an industrial engineer; he sought the status of *savant*: he constructed a veritable *epistemology* of statistical quality control, relating his development of ideas and methods to the grand scientific laws of nature in a form which suggests Laplace's Philosophical Essay on Probabilities.[23] In a communication of 1929 to the *American Society for the Advancement of Science*, an important American scientific society, he posed three *postulates* (sic) in order to introduce the concept of *constant system of chance causes* (in modern language, we say: *stationary random system*):

> "Postulate 1. All chance systems of causes are not alike in the sense that they enable us to predict the future in terms of the past.
>
> Postulate 2. Constant systems of chance causes do exist in nature.
>
> Postulate 3. Assignable causes of variation may be found and eliminated."

These propositions are destined to serve as the theoretical basis of the development of statistical quality control. Each postulate is supported by several examples, some drawn from statistical physics and demography, the others from the experience of engineers (which is the basis of the third postulate, a principle of action). If it had been published today, the text would probably be judged a fantasy or megalomaniac; as a matter of fact, it connects things which appear to us disproportionate and heterogeneous: engineers seeking to regulate machinery, on the one hand, and cosmological or metaphysical principles on the other hand. Is it really necessary to invoke so general a set of propositions in order to justify a method which is by itself totally understandable? But Shewhart, in fact, exploits as far as possible his experience and knowledge as physicist in order to bring all modern science of the time in support of his approach. The mobilization of, in the words of B. Latour, these "allies de poids" might explain why Shewhart's theories have never been attacked with respect to their scientific legitimacy: such critique would have to contend with the weight of all this science

[23]A connection which is not simply due to chance, Shewhart having been introduced to this work of Laplace by E.C. Molina, of Bell Labs, a mathematician and connaisseur of the history of probabilities.

with which Shewhart's texts are amply loaded.

But the weight of these scientific allies does not suffice to explain the success in practice of Shewhart's method. Yet to be demonstrated is the method's technical feasibility and economic viability -- criteria which are critical and prerequisite to industrial acceptance. In an extremely dense article, Shewhart adds on some economic arguments in favor of statistical quality control: reduction of the cost of inspection, reduction of the cost of wastes, maximization of the benefit of large scale production, achievement of uniform quality even in the case when one performs destructive tests, reduction of the tolerance limits when the measure of quality is indirect (then making use of correlations).

Shewhart however is not a very gifted popularizer nor a great communicator. In his whole career he only published two books. The first, in 1931, pulled together all of his prior articles in an opus which was very dense and difficult to read. It constitutes a reference work, a work of legitimization, but certainly not an operator's manual... It has been enormously cited, but without doubt little studied in fact by practitioners because it raises more questions than it offers responses. The second book is even more "philosophical", concerned as it is with the theory of scientific knowledge and operationalization of concepts.

In view of these works, it is evident that it is not the personal charisma of Shewhart (so theoretically inclined) nor his efforts at promotion which can explain the success of statistical control of fabrication. It would require the help of engineers more oriented toward practice who, coming together in committee, would produce some operational standards. A true division of roles thus appeared among the different agents intervening in the process of promotion. The weight of Bell System, of its research arm, Bell Labs, and its production division, Western Electric, is also evidently an important reason for the promotional success of the method[24].

The very theoretical character of some of Shewhart's works ought not, however, lead us to neglect the importance of the modification he has accomplished in the domain of ideas. In

[24]A French example provides an element of comparison : Maurice Dumas, an engineer who developed an accurate probabilistic thinking about acceptance sampling in 1925, did not meet with any success. He was not backed up by heavy industrial forces.

fact, beyond the pure transfer of reasoning and observations drawn from the field of theoretical physics, he develops as well an elaboration addressing challenges specific to the world of industrial production. In the first place, he takes economic factors into account; if the best strategy when faced with the randomness of production is to eliminate the assignable causes of variability and to maintain as constant as possible the conditions of fabrication, the cost of these operations ought to remain "reasonable" in the sense that it satisfies the judgement of the engineer. Certainly, Shewhart, from the perspective of economic criteria, did not take the articulation of the development of quality very far but his colleagues Dodge and Romig, with whom he was closely associated, published in 1929 a method of control via sampling which rests explicitly on an optimization of the costs of inspection. The preoccupation of management with costs is thus well represented in this engineering milieu and it comes to be expressed in operational terms.

Then too, Shewhart completely reformulates the notion of *control* with the aim of taking into account the indeterminism of phenomenon, notably the fundamental fact that *a controlled quality is a variable quality* and not always equal to a preestablished standard:

> "For our present purpose a phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon will be expected to vary in the future. Here it is understood that prediction within limits means that we can state, at least approximately, the probability that the observed phenomenon will fall within the given limits."[25]

The fundamental principles are now fully integrated into the daily practice of the quality control function.

3 The mode of engagement of objects in action.

We have seen how in the construction of the theory, Shewhart articulates, on the one hand, science and on the other hand, some objects which link with practice: the carbon microphone demonstrates the necessity to resolve a problem of fabrication, the graphical object in the form of the control chart suggests a method which appears intuitive and easy to apply. But at this stage of the analyses we have only examined the matter from the point of view of Shewhart, the initial promoter, who expresses himself with a good dose of rhetoric. That the method appears to be useful in practice might derive from Shewhart's rhetorical abilities or from the helpful advice he received from his engineering colleagues with whom he associated and who consulted with him -- since we have seen that Shewhart was more oriented toward theory. From an examination of the rhetoric of the promoters alone we can, in fact, deduce nothing about the actual conditions for applying the method.

To address this question, requires that we analyze the way in which the method was put into practice and received by users. We avail ourselves of some witnesses who, although there are lacuna, none the less, allow us to draw some interesting conclusion when we place what they have to say within an appropriate conceptual framework. Let us sketch our framework for analysis.

It is a question, fundamentally, of a study of *reception*. It requires radically displacing our point of view which, up until now has been that of the promoters, in order to adopt that of the users. The user confronts two types of factors: the discourse of promoters and the object for putting the proposed method into practice. The industrial user is above all anxious to know if the method works in the context of the shop floor; a priori, then, he is going to listen to the words of the promoters with distrust knowing that they contain a good dose of rhetoric. He will ask for proof, of trustworthy witnesses, of results of tests... But those are *discursive* elements which, if they can attract the attention and interest of industry, ought to be dissociated from *trying out* the method, an engagement in practical action which puts the objects to work. We will try to show that the test of the control charts exhibited a decisive power of conviction on people, for example in the training of professionals. This will be the focus of the first point: the control chart as new cognitive tool. We will then examine how the argument of promoters was reinforced by recourse to other objects than the control chart, such as urns to simulate random sampling, which were utilized in the training sessions but not in the workshops. In a third part we analyze the compatibility among the ensemble of

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[25]Shewhart 1930, *op. cit.*, p. 4.

objects associated with statistical control (notably the directions for use) and the organizational structures of the enterprise, the division of competencies and tasks. Finally, we will see how the objects engage the theory in the daily life of the enterprise.

3.1 The control chart as new cognitive tool.

The control chart exhibits some properties which are associated with a new way of perception: it renders visible and tangible some phenomenon which before were hidden. A standard control chart (cf fig. 3) allows one to follow two tendencies of the quality characteristic: its mean and its standard deviation. If the mean is a relatively intuitive notion, the standard deviation is not; one can conceive of the idea but one is at a loss to give it a precise mental representation without recourse to an image such as a histogram. Now the control chart offers the viewer, laid out on a plane sheet of paper, the concept of dispersion showing the limits that this dispersion ought not to exceed as long as the production process remains under control. It presents, in a perfectly visible and sensorial way, the variability of the fabrication process as it proceeds in time. Note that it does not use the representation of the histogram which would not be a very effective way to follow the evolution of the standard deviation in time.

If we go a little more into detail. the control chart also represents other more abstract notions: the variability of the mean and the variability of the dispersion. What is the variability of a dispersion, of the standard deviation? To understand this concept requires explaining the process of sampling, to understand that one estimates, with each sample made, the dispersion of the ensemble of the population, that this estimation displays a variability due to the sampling process itself. In brief, a succession of difficult reasonings, that it would be impossible to mentally deploy in the course of repetitive work. Now the control chart presents these not very intuitive notions, without need of a mental representation on the part of the user. Here resides the tour de force: thanks to the control chart there is no need to rely upon the mental powers of the worker to manage dispersion. The statistical notion of dispersion, which is constructed in the theory, has thus acquired a unique, visual representation.

The control chart thus allows the transformation of a complex ensemble of abstract reasoning into a work procedure which calls upon the most general faculties of representation (vision) and on some elementary, arithmetic operations. The analysis presented above certainly does not rest on first hand empirical observation; we have constructed it from the thought process we have projected upon the user. But it is necessary to emphasize that such observations are practiced by certain researchers in the cognitive sciences and distributed cognition;[26] the principle here is to describe exactly, by means of a phenomenological observation, what the subjects do, what elementary cognitive means they put into play in the use of instruments of work, with the aim of reconstituting their "mode of use" of the objects - and not the theory that an engineer could see behind the functioning of these objects. In the routine of the workshop, once statistical control is in place, it is not the theory which serves, but the control chart object and its associated organizational procedure which governs its use. The procedure, applied in an automatic way, requires no reference to statistical theory. The activity of the worker can be analyzed as a succession of elementary cognitive operations: select a sample, make the measurements, then the computations, record on the graph, look at the data, conclude...

But, from another angle, it would be false to consider that the control chart object allows one to completely avoid the theory, to relegate it to the backstage. In fact, if we readily allow that the worker on the line is not concerned with the theory of statistical control in his day to day activities, it is certainly not the same for the engineers who try to understand, by means of their individual cognitive powers (rooted in the scientific concepts that they ordinarily employ), how these objects work, how they produce tangible results. It is to this audience, as well as their supervisors, that the training sessions are directed where each participant is confronted with some "pedagogical" artifacts which generally have a very convincing effect, according to what the trainers report[27].

Among these artifacts, we must in particular mention the *bowls*. They were filled with numbered uniform "poker chips" in such a way so that, when one made a random selection from the lot, one simulated the random sampling of a normal distribution (following the law

[26] see note 3

[27]For example, Grant E.L., and Leavenworth R.S., 1972: *Statistical Quality Control*, McGraw Hill, International Student Edition;
Peach P., 1947: *An Introduction to Industrial Statistics and Quality Control*, Raleigh, N.C.: Edwards Broughton.

of Laplace-Gauss), or of a uniform distribution, or even a triangular distribution. This type of simulation has frequently been used by statisticians either to test the results obtained from analysis or to demonstrate in a vivid way the “law of chance”.[28] In the science museum are exposed various apparatus inspired by the same principle which always provoke astonishment on the part of visitors: is it not always fascinating to observe order born out of apparent disorder?

We find in this an effect of the type “to test it is to adopt it”: the astonishment that a new user experiences in observing how “it works” is an important psychological factor which explains the often militant character of partisans of the statistical method.

One consequence of this confrontation with this artifact, generally successful in the training sessions, is that, for the engineers so trained, the control chart object becomes an incarnation of the theory. The control charts in their routine functioning (as they work well) constitute a permanent validation of the theory; it becomes as impossible to doubt as the theory of the steam engine... We observe here a circular causal chain: the object is founded on the theory, which in turn is founded on the object’s functioning, and so on... But similarly, it is necessary to recall -- because this shows the multiplicity of meanings which an object can bear-- that the object engages the theory in a different way according to the level of knowledge of each individual: the worker sees in it only a procedure. Ignorance of the theory does not prevent him from putting the object to use in an autonomous way; but, on the other hand, the theory can only make its proofs through the object which it depends upon.

3.2 Objects in support of rhetoric.

The acceptance of statistical control developed along two paths: through persuasion and effect of the rhetoric of promoters and new militant users of statistics and by confrontation with the objects themselves, an aspect of the experience of reality. But in all the material put to use in this historical analysis, it is impossible to separate the two types of effects: all accounts of confrontation with the objects, published in the technical journals, have rhetorical content.

[28] Stigler S. M., 1986: *The History of Statistics*, Harvard University Press.

In order to get beyond this difficulty, we observe the way, in the rhetoric, the objects are described and what objects are chosen and privileged in support of the argument made.

We find a great number of texts which recount the application of the method. Theses texts lead the reader to mentally project him or herself into the situation in confrontation with the objects and to simulate this experience. The method of statistical control is put to a real test, the text exposes the conditions and renders account of the results. These represent, if not ostensibly "advertising", elements upon which the readers can base their opinion of the method.

A second category of texts concerns experiments with the method in a "scientific" context, that is to say in a laboratory. Shewhart has so utilized the urns of normal, uniform, and triangular distributions, discussed above, in order to test the method of rational subgroups (which would take too many words to explain here) which is the basis of the control charts. He has published the results of 4000 drawings from each of these three distributions; his tables continued for a long time afterwards to serve as a reference since we find them still used in a manual dating from the 70's. We note that in the first French article[29] dating from 1925, we find a similar presentation which the author employs in order to confirm the results of his analysis. These explanatory objects are only engaged, by the reader, via a description in words, sketches, lists of numbers, tables of results of analysis. The reader does not have the original objects in front of him and can not manipulate them in order to verify what he is reading. To understand the experiment, he has to do so via mental representations with full confidence in the author. None the less, these elements are taken as proofs.

Along side these objects which engage the theory in putting the method into practice, we should also pay attention to those which serve to establish an argument, and which the reader encounters in the textual form of accounts of experiments.

With respect to the arguments about the economic advantages of the method, we see that the objects exhibited are often less convincing. Essentially, here we find some evaluations which are not always quantitative. More than the objects, this which brings acceptance is the effect of the example: the fact that one firm as important and serious as Western Electric had undertaken between 1922 and 1924 a campaign of improvement in quality by applying statistical methods constitutes a powerful argument... It has behind it all the weight of the enterprise.

But these experiences are not very numerous, so it is necessary to extrapolate. Shewhart shows, making use of graphs and series of numbers which measure the nature of quality, some situations which are not "under statistical control" and where he must intervene to set matters right. But he takes care to state that it is necessary to "use your good sense" and not to undertake action to improve the quality if the gain in doing so is not greatly superior to the cost of doing so. This reasonable attitude is called "engineering reasoning". Here thus the engineer is brought into the picture to counter balance the scientist who might be a bit too much of an idealist; in this way the entrepreneurial reader would be reassured. We know furthermore that Bell Labs was staffed with as many engineers as academics, this which would give a certain credibility to Shewhart's argument.

3.3 Objects in the organization of the enterprise.

At work, the objects prescribed by the theory of statistical control of fabrication call into question certain organizational requirements on the shop floor and its social life. The objects which might lead to theoretically best performance are often too difficult for a handworker to put into use, and hence might, if adopted, lead to errors.

Thus the "sequential plan" which leads in theory to very important gains with respect to the size of samples is little utilized because it requires too many manipulations and thus risks being applied wrongly. These plans are the work of a brilliant mathematician, Abraham Wald, who developed them under contract with the American government during the last world war. But without doubt this mathematician did not have a sufficiently concrete sense of context, and the methods of the engineers of Bell have continued to be favored in industry. In looking back, the efforts of Wald have had some very important consequences for decision theory and have significantly contributed to progress by scholars...

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[29] Dumas M., 1925 : "Sur une interprétation des conditions de recette", *Mémorial de l'artillerie française*, tome 4, fasc. 2., pp. 395-438

In the context of the shop floor, it is not good to leave chance much opportunity to arise and the methods of statistical control were rapidly standardized. This process of codification of instructions may be compared with its operation in a military organization: in the artillery, one finds a handbook for the gunner, another for the staff sergeant, another for the officer... and in the enterprise, we find a scientific treatise for the engineers, a popularization for the directors, a technical work for the supervisors (which does not reproduce the derivations of the theory but gives examples), and the notice of instructions for the machine attendant. Each of these works gives some rules of conduct, but with less and less freedom of maneuvering as we descend towards the base of the hierarchy. The engineer can choose among different types of control charts, the supervisor among different ways to make a measurement, but the worker only has one rule to apply: to call the machine setter if the points recorded on the chart exceed the control limits and to continue as before if they do not. Even the random drawing of the members of the sample is subject to strict regulation with the aim of avoiding the possibility that the worker introduce, consciously or unconsciously, some personal strategy which would produce a bias in the control method: the experts advise as a matter of course the use of the tables of random numbers but think these too present too much margin of maneuver and thus the possibility of error; so they have invented numerous ingenious apparatus which facilitate randomly drawing a sample with a minimum of intervention of whoever does the task.

The development of statistical control is thus mixed up with the division of labor and responsibilities on the shop floor. Apparently this mixing has been carried through with success, that is to say, in a way acceptable and in harmony with the social order within the enterprise. This is certainly one of the strong points of the successful development of statistical quality control, that it ably lends itself to this decomposition across the hierarchial structure, which assigns to each person a task corresponding to his social rank and level of education. Not all management methods have had this capacity which explains why a number have been rejected.

Once this decomposition is conceived and put into practice it becomes a factor which anchors statistical quality control in the firm: it is then integrated into the organizational system, it is no longer possible to touch one element of the system without touching many others and the cost of changing the system becomes very great.

3.4 Objects engage theory in social process

The object, while seen as the incarnation of theory for those in the know, can find itself engaged in other relationships which were generally not foreseen by the initial promoters of the theory and which appear in the course of application of the method. The theory finds itself thus tied to new objects, taking part in new relations which contribute either to consolidate or destabilize the theory according to the circumstances.

We take an example: statistical control changes modes of relationships on the shop floor. One of its advantages, according to the experts, is that it in fact allows one to decide, on the basis of objective and impersonal criteria, at what moment the machine has strayed off course; this means that the worker, on the basis of his reading of the control chart, can decide to call the machine setter or to continue production as usual. The machine setter or supervisor can thus no longer reprimand the worker as freely as they choose when something goes wrong. On the contrary, the machine setter can find himself in a difficult situation if the control chart shows that he has not been able to set up the machine as well as required.

Statistical control can equally be used to modify relations among fabrication, inspection, and the department of product design. Control charts provide a picture of the precision that the machines are capable of attaining and it would thus seem logical that the design department should take this into account in setting the tolerances. If not, a good number of products would not be in conformity with specifications, it might require eliminating the nonconforming ones as waste. Before the introduction of statistical quality control, the design department was rarely called into question: the responsibility for bad parts lay on the shop floor, this which provoked disputes between production people and inspectors. According to some witnesses, statistical quality control has allowed breaking this closed loop in implicating the design department and allows resolution of questions of this sort by providing some tangible elements for discussion (the measures of quality and their statistical distribution).(167)

A second example shows how theory, engaged in the social process via its associated objects, acquires a social image which was not foreseen at the outset. The promoters of quality control at Ford, in 1950, produced a brochure intended for the training of its personnel and in it statistical quality control was associated with images of improved social standing; medicine, systems of alarm. The analogy with tracking the state of health of a patient was based on the similarity of the graphic form of the control chart and the sheet recording the temperature of a patient:

> "Charting is a running picture which keeps us up to date on the quality of work we turn out. Some people compare it with a patient's temperature chart in a hospital. Nurses take the patient's temperature at regular intervals. They plot each reading on a sheet of graph paper and connect the points by a line. When the doctor arrives to check on the patient's progress he notes the graph, which he considers a good general sign of the patient's state of health..."

In analogy with the systems of alarms, statistical quality control is described poetically as a method which signals displacements from the ideal quality:

> "It would be wonderful to have a series of lights and bells hooked up to every machine and operation. Then when our work would get 'just a hair' away from perfect, the bells would ring and the lights would flash..."

Through this process of association of statistical control objects with other clearly social objects, a social perception of the new theory develops and finds itself anchored in a social reality which had been foreign to it. It is important to emphasize that these associations and anchorings are made through the use of the methods and tools of statistical control by social actors; they are not inherent in the objects themselves. To take an analogy from linguistics, it is the context which weaves a sense to the message; and through this phenomenon of social anchoring, this supplementary meaning ties the message to the object in a permanent way. The theory of management then becomes much more than a body of knowledge: a symbol bearing a value which it is no longer possible to separate from it.

4 Conclusion

The history of statistical quality control shows that two processes of construction have occurred in parallel: on the one hand we have the scientific construction of new properties of industrial products (for example the dispersion of characteristics), on the other hand the construction of objects permitting one to see these new properties and to manage them. Correlatively, the object has thus an essential double use: it provides faith in the solid foundation of theory, and allows one to act in the real world. Through the use of objects and the acts of training which have accompanied this, the individuals have definitely acquired new aptitudes such as the ability to perceive a dispersion in reading a graph.

The case addressed here illustrates the relationship which exists between control theories and the objects which serve to put them to work. This relationship is both trivial and enigmatic, according to the way which one approaches the subject. It is trivial for the statistician: the objects are only the embodiment of the theory and it is the latter which is important, not the objects. The objects are only an aid, a prosthetic device, a material extension of the mind. But seen from the workshop floor, these objects are the tools one works with; the theory is as far removed from the floor manager as from the worker and both have no means for understanding that theory in the same way as the statistician. The effective factor is then the object's capacity to represent something -- in this example, the world which is represented is abstract and invisible -- the world of statistical parameters. But the representation itself is surely real: e.g., the designated points on a graph, some lines and axes labeled with different numbers. Metaphor allows one to give various, isomorphic, meanings to these geometric figures; e.g. it is necessary to operate in a way which keeps things on a path defined by the two limits of control; to leave the route is an accident, the cause of which it is the job of the technicians (and not the worker) to uncover.

The control chart is a good example of an object which materializes a control objective. This object is subject to human cognition, the understanding of its functioning is thus extremely complex. One can however gain a little clarity in locating it among other modes of control according to its degree of materiality. The spoken word is of minimal materiality, the walls of a prison at the other extreme. When a superior gives an order to his subordinate, there remains no material trace. A higher degree of materiality is attained with a written instruction. The order or the rule is written "somewhere" and, if need be, can be exhibited. Maximum materiality is attained by the prison where the management of bodies is inscribed, as Foucault has shown, in its architecture and spatial arrangement. Prisons, hospitals, schools of the 19th century, are good illustrations of the methods of management and control of persons; by their materiality they act directly on the body and indirectly on the mind. Think too of the example of the bridge analyzed by L. Winner. In public transportation today, methods for managing people use procedures similarly acting on the body, even if they are less deliberately provocative: corridors and walkways within the metro, escalators, barriers and other guides. There is a continuity among the corridors which layout the obligatory path of the traveler and the indicator panel lights of the stations, the signal system which indicates the trajectories that the managers of the stations hope will be used by travelers.[30] All serve the same ends. The difference is that the trajectories shown by the signaling system can be modified as a function of circumstances, with the location of trains for departure, etc. These are immaterial walls which require the use of the cognitive faculties of the travelers.

These different examples of objects produced with the intention of control apparently work in different ways: Walls can't be crossed, but one can act as if one has not heard what a colleague at work has said (this is more risky if the speaker is a superior). How to envision all of them as one thing - in so far as they are objects serving to control? We propose the concept of sign in the sense of C.S. Peirce. A sign according to Peirce does not have a unique, well defined interpretation; it is not a signal. It is a point of departure of a process called "semiosis" which might go on indefinitely. A wall of a prison can signify, for a prisoner thirsting for freedom, an aim in his life as prisoner - to escape - this which will help him at least to remain in a state of mental alertness (at least according to the police literature). The effectiveness of a control object is not tied so much to its materiality as to the meaning which it takes on when it is interpreted by people. The focus of research thus finds itself displaced towards the study of situations which, we make here the hypothesis, frame and orient the individual and the collective processes of semiosis. In particular, in the context of work within an enterprise, it seems necessary to study work practice, that is the cognitive activity at work as it is continuously engaged in interaction with the work environment. Through research of this kind, we can hope to understand better how the cognitive or material objects

[30] These remarks are based on an empirical study realized within a large Parisian station with the support of the

engage the person at work and sustain this engagement through a feedback process.

transport agencies.